# 5.0 FORCED RESPONSE PREDICTION

**BACKGROUND**

The responsibility of the Forced Response Prediction Action Team (FRAT) is to foster collaboration between individual HCF forced response efforts and the Instrumentation and Component Analysis ATs in order to determine alternating stresses to within 20%. The Forced Response AT provides a means for technical coordination and communication between active participants involved in HCF unsteady aerodynamics and blade response technologies. Annual technical workshops have been organized and workshop summaries are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Forced Response AT members meet as required to review technical activities, develop specific goals for forced response programs, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Forced Response AT keeps the TPT Secretary informed of AT activities on a frequent basis. This AT includes members from government agencies, industry, and universities who are actively involved in forced response technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate.

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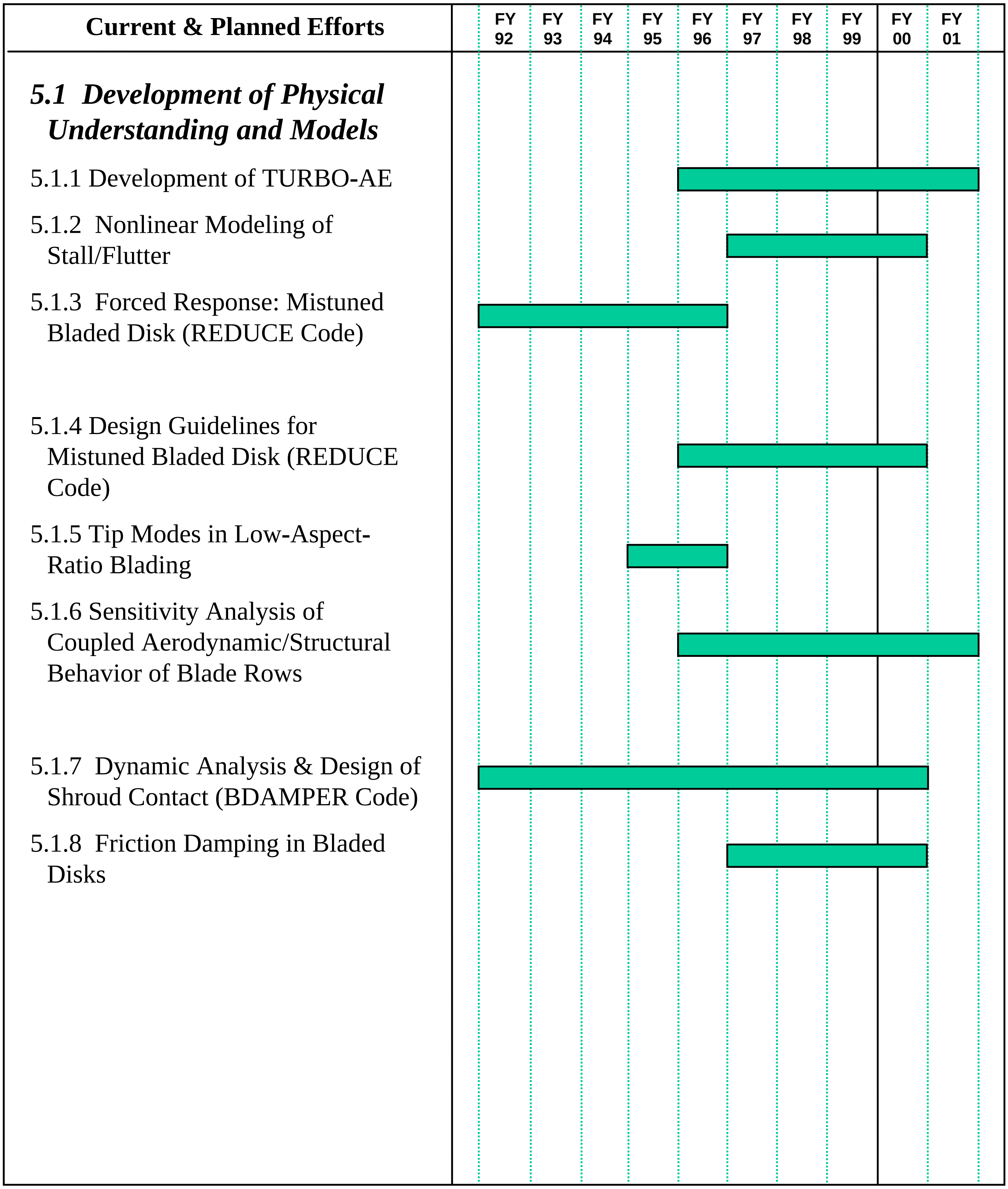
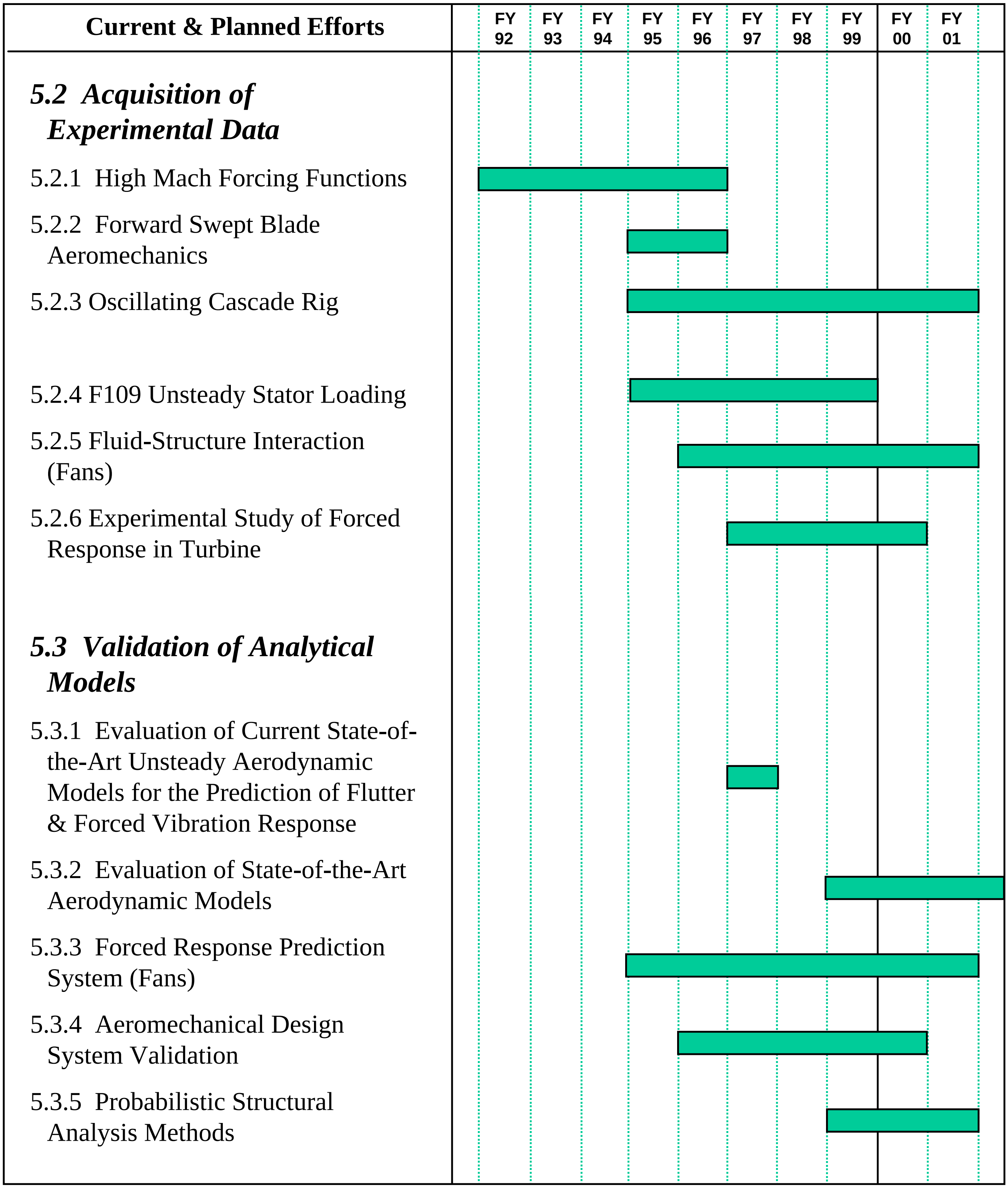
**INTRODUCTION**

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

# Forced Response Prediction Schedule



# Forced Response Prediction Schedule (Cont'd)



# 5.1 Development of Physical Understanding and Models

Predicting forced response is difficult due to the lack of Computational Fluid Dynamics (CFD) fidelity and structural modeling accuracy. The purpose of the following projects is to develop the necessary modules for improved forced response prediction

## 5.1.1 Development of TURBO-AE

*FY 96-01*

**Background:** The TURBO-AE Propulsion Aeroelasticity code is based on a three-dimensional unsteady aerodynamic Euler/Navier-Stokes turbomachinery code called TURBO. The structural dynamics model of the blade in the TURBO-AE code is based on a normal mode representation. In the Flutter version of the TURBO-AE code, a work-per-cycle approach is used to determine flutter stability.

**Recent Progress:** The development of the Flutter version of the TURBO-AE code has been completed, and validation by industry is ongoing. The development of the Forced Response version of the TURBO-AE code has started. Future planned activities that have not yet been funded include multistage analyses and new turbulence models.

**Participating Organizations:** NASA Glenn

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## 5.1.2 Nonlinear Modeling of Stall/Flutter
*FY 97-00*

**Background:** The objective of this project is to investigate the use of reduced-order modeling (ROM) techniques to simulate linear and nonlinear stall flutter in cascades. Research will be conducted in three main areas: (1) the development of a time-domain, linearized Navier-Stokes analysis; (2) the development of an efficient eigenmode extraction code for large systems of equations; and (3) the development of reduced-order modeling techniques to model nonlinear unsteady flows, especially phenomena such as hard flutter boundaries and limit cycle behavior.

**Recent Progress:** Use of the Harmonic Balance technique for the nonlinear flow solver has been investigated. A frequency domain Proper Orthogonal Decomposition (POD) technique has been developed to compute basis vectors and linear ROMs of unsteady channel flow. These efforts are potentially much faster than conventional time-marching solutions and are computationally efficient. Using the POD technique, a nonlinear ROM will be developed for unsteady viscous flow in cascades. Analysis codes will be transitioned to industry through GUIde Consortium.

**Participating Organizations:** GUIde*, Air Force Research Laboratory (AFRL), NASA

> ***(*) About GUIde:*** *The GUIde Consortium was formed in 1991 when a number of companies joined with Carnegie Mellon University and Purdue University to form a partnership that would result in improved technology for understanding the problem of forced response in turbine engines. The acronym GUIde stands for Government, Universities, and Industry working together for a specific goal. The consortium is a precursor to the current national HCF program. The consortium consists of members from USAF (Air Force Research Laboratory (AFRL) and USAFA), NASA, all four major engine manufacturers (GE, Pratt & Whitney, Allison and Honeywell Engines and Systems) and academia (Ohio State, University of California at Davis, Purdue, Carnegie Mellon, University of Michigan, Duke, and Notre Dame). Together, the consortium works to address shortfalls in alternating stress prediction capability with the academic and industrial members developing or validating new codes funded by the government and industry. Some of GUIde's early codes are currently being integrated into the design systems of the engine manufacturers.*

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### 5.1.3 Forced Response: Mistuned Bladed Disk (REDUCE Code)
*FY 92-96*

Blade mistuning is the small, random, blade-to-blade variation in geometric and material properties that is unavoidable in bladed disks due to manufacturing tolerances and in-operation wear. Mistuning can lead to localization phenomena in which certain blades vibrate with higher amplitudes than other blades. Under this effort, a reduced-order modeling technique for mistuned bladed disks was developed. The resulting code, REDUCE, can calculate natural frequencies and mode shapes for a tuned case and for a prescribed mistuning pattern. REDUCE allows the user to obtain a frequency sweep output for the maximum blade response amplitude or for all blades. A Monte Carlo analysis is performed to determine the blade response amplitude and deviations. Pre- and post-processing capabilities allow for use of NASTRAN and ANSYS files. The REDUCE code version 1.0 has been transitioned to the industrial GUIde members.

**Participating Organizations:** GUIde

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### 5.1.4 Design Guidelines for Mistuned Bladed Disks (REDUCE Code)
*FY 96-00*

**Background:** The objective of this project is to develop a program for analysis and design of mistuned bladed disks based on REDUCE (first developed under GUIde I, with an updated version released each year).

**Recent Progress:** Version 2.2 of REDUCE has been released to GUIde members. New features in REDUCE 2.2 include an enhanced capability for fine-tuning the reduced order model to match Finite Element Model natural frequencies, the ability to input a complex forcing vector to capture local phase differences in the applied blade forces, a new capability for outputting/inputting the reduced order model to/from a single file, and improved support for post-processing the displacements and stresses in Finite Element coordinates. An experimental investigation has been initiated to generate validation data for mistuned and intentionally mistuned systems. Modifications and improvements will then made to the REDUCE code based on these findings. In addition, a more powerful, accurate, and efficient reduced order modeling technique has recently been developed. The next-generation code (TURBO-REDUCE) that implements this new method is currently being written.

**Participating Organizations:** GUIde

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## 5.1.5 Tip Modes in Low-Aspect-Ratio Blading
*FY 95-96*

The objective of this project was to develop a basic understanding of sources of variability in high-frequency motion in low-aspect ratio blades, and to develop codes based on this research. The two thrusts of the research were: (1) to understand the effect of taper angle and bluntness of the leading edge of the airfoil on the vibratory response of high-frequency tip modes, and (2) to develop an understanding of the manner in which closely-spaced modes interact to produce highly variable response. For the first thrust, using a tapered beam as a first-ordered approximation for a low-aspect ratio blade, it was determined that the magnitude and location of maximum stress were functions of the truncation factor. For small truncation factors, the response of a high-frequency mode was extremely sensitive to variations in the tip thickness. For the second thrust, for an airfoil with two modes of nearly equal frequency, the modes are highly sensitive to minor variations in blade geometry. Codes developed under this effort have been transitioned to GUIde members.

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## 5.1.6 Development of Aeroelastic Capability for the TURBO Code

*FY 96-01*

**Background:** TURBO is a three-dimensional unsteady aerodynamic Navier-Stokes turbomachinery code for propulsion applications. Mississippi State University developed the TURBO code under a grant from Glenn Research Center. For aeroelastic calculations with TURBO, the structural dynamics model of the blade is based on a normal mode representation. For flutter calculations, a pre-processor is used to interpolate modal displacements onto the TURBO grid and to generate the deformed grid. Then, a prescribed harmonic blade vibration with a work-per-cycle calculation is used to determine flutter stability. For forced response calculations with TURBO, the aerodynamic interaction between adjacent blade rows is modeled either as (i) a rotor-stator interaction with multiple passages per blade row, (ii) a rotor-stator interaction with phase-lag boundary conditions which requires modeling only one passage per blade row, or (iii) a wake-blade interaction with the influence of the upstream row represented as an unsteady inlet excitation.

**Recent Progress:** The development of the flutter capability for the TURBO code has been completed, and many validation cases have been run by industry. The development of the forced response capability for the TURBO code is nearly completed, and some validation cases have been run. Planned future activities (subject to funding availability) include extension of TURBO to multistage analyses and analysis of centrifugal machines.

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## 5.1.7 Dynamic Analysis & Design of Shroud Contact

*FY 92-00*

**Background:** The objective of this project is to develop a program to predict blade vibration for rotors having shrouds and/or platform dampers (friction dampers). The completed GUIde I effort was instrumental in the development of BDAMPER, which facilitates analysis of blade-to-ground dampers, blade-to-blade dampers, shroud contact interfaces, and wedge dampers. The GUIde II effort focuses on the stick-slip transition for elliptical motion in the shroud contact plane.

**Recent Progress:** Under the GUIde II effort, development of specific BDAMPER modules is continuing. BDAMPER 6.0 has been delivered, transitioned to GUIde industrial members, and successfully utilized in damper redesign. Analysis of constrained and complex mode shapes and initial 3D kinematics was completed earlier this year. Work in 3D contact kinematics continues, and advanced subroutines for BDAMPER will be transitioned to industry. BDAMPER 7.0 will be transitioned to industry in early 2000.

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## 5.1.8 Friction Damping in Bladed Disks

*FY 97-00*

**Background:** The objective of this project is to investigate the extreme sensitivity of shrouded bladed disk systems to small changes in the input variables. The final result will be a set of design tools and guidelines that can be used to develop robust shrouded bladed disk systems.

**Recent Progress:** It was shown analytically that shrouded bladed disk systems can be very sensitive to small changes in the friction slip loads. For example, under certain conditions, a perturbation in the slip load of as little as 1% can cause a 30% change in the vibratory response of the blades. The conditions under which high sensitivity can occur and the underlying physics that causes it have been identified.

In addition, a more efficient and accurate reduced order model was developed that uses a subset of nominal modes to represent the response. The new approach makes it relatively easy to include aerodynamic coupling, mistuning, and friction nonlinearities in the analysis. The resulting code is currently undergoing validation evaluation.

**Participating Organizations:** GUIde

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## 5.2 Acquisition of Experimental Data

To validate advanced prediction models, experimental data is needed. The objective of the following projects is to obtain data necessary to validate modules for improved forced response prediction.

### 5.2.1 High Mach Forcing Functions

*FY 92-96*

The objective of this project was to acquire and analyze data defining the forcing functions generated by the wakes from rotor blades operating at high subsonic and transonic Mach numbers. Data for both the near and far wake were obtained in the Purdue High-Speed Compressor Facility (Fig. 34).

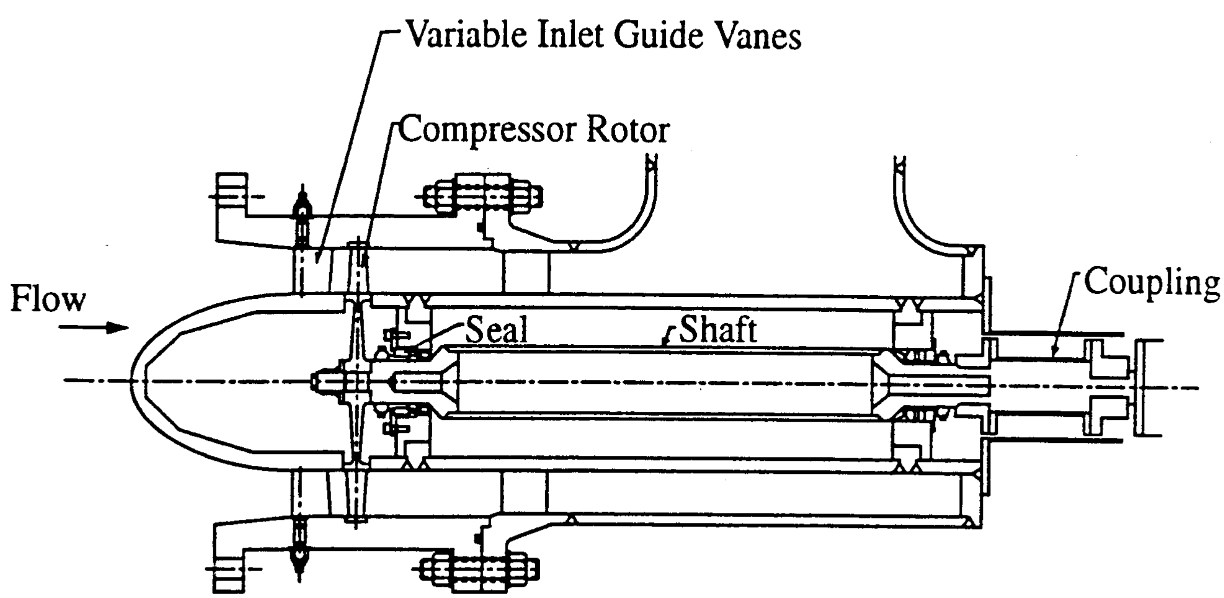


**FIGURE 34.** Purdue High-Speed Compressor Configuration: Single-Stage, 2/3 Hub-Tip Ratio Design, 18 Variable Inlet Guide Vanes, 19 Rotor Blades, Rotor Diameter 30.48 cm (12 in)

Concurrent to the experimental investigation, fundamental modeling was performed, utilizing current and advanced forced response unsteady aerodynamic models. The experimental data sets were acquired to provide benchmark data for validation of advanced computational fluid dynamic analysis codes. Flow topics which were investigated included rotor wake and potential forcing function blade row interactions, inlet guide vane (IGV) wakes, high-speed rotor wake vortical and potential forcing functions, transonic flow effects on acoustic modes, airfoil row wake interactions, and separated flow effects.

In this study, completed in 1996, the potential gust component of the rotor wakes upstream of the rotor was found to be dominated by the first harmonic component, with small contributions from the second and third harmonics. Higher harmonics of the vortical gust component of the rotor wakes measured both in and out of the IGV wakes are found to be significantly reduced in the IGV wake regions and decay at a uniform rate due to viscous diffusion. Wakes were predominantly vortical for a Mach number near 1.0 and combined vortical-potential for supersonic flows. Interaction of the rotor wake with the IGV wake has a significant effect on the characteristics of both the IGV and rotor wakes. When the rotor blade wakes are in-phase with the IGV wakes, the IGV wake velocity deficit, semiwake width and total pressure losses increase.

**Participating Organizations:** GUIde, NASA

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## 5.2.2 Forward Swept Blade Aeromechanics

*FY 95-96*

This effort involved application of available design/analysis tools to evaluate and predict the aeromechanical performance of a forward-swept rotor 1 of a two-stage test vehicle with inlet guide vanes. The rotor was tested at the WPAFB Compressor Research Facility (CRF) with instrumentation to measure and monitor the aeromechanical and aerodynamic behavior, both natural and forced. The aeromechanical goal of this effort was to evaluate the current aeromechanical design tools and practices needed to support the successful use of forward-swept blading. Also of interest was identification of unique aeromechanical problems in the design, in current design practice, or in the application of existing design tools.

Based on the testing results and comparison to the analytical predictions, the following conclusions are drawn. Empirical curves of current design practice are inadequate to predict the stability of forward-swept airfoils. The GAP software and analysis process is overly conservative for stability analyses. The NOVAK2D software and analysis process is a good tool but limited to nominal and low operating lines. The SIFOR forced-response analysis process yields fair correlation. Low-order modes have the best comparison. All tools and analysis processes need further development and improvement. Additional tools should be developed that are more accurate and applicable to more operating conditions, especially the high operating line.

This program produced a large amount of detailed data, and much of it was reduced and reviewed/evaluated. The acquired data add considerably to the available aeromechanical database, particularly for forward-swept airfoils. These data are available for, and will be very valuable to, the future improvement of existing analysis tools, design practices, and airfoil designs. Development of new, more powerful tools will benefit from this program and the data acquired. Enabling technology developed by this program will contribute to significant improvement in fan and compressor aerothermodynamics through implementation of forward-swept blade designs with lower development risk and cost.

**Participating Organizations:** Air Force Research Laboratory (AFRL), General Electric

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## 5.2.3 Oscillating Cascade Rig

***FY 95-01***

**Background:** The NASA GRC linear oscillating cascade is one of a very few test facilities dedicated to unsteady aerodynamics of oscillating airfoils. The facility is used to investigate unsteady aerodynamic phenomena in an oscillating row of airfoils modeling self-induced cascade flutter. Experimental data acquired in this facility serve as benchmark sets to validate CFD codes for predictions applicable to real turbomachines, so that the data must be of the highest quality and reliability with characteristics sufficiently close to those encountered in annular cascades of real machines. However, achieving flow identity in linear and annular cascades is a very difficult task even for steady flow conditions.

**Recent Progress:** Lately, the cascade facility has been used to investigate flowfield about airfoils typical for blade tip region of modern high-speed fans. The airfoil has an 'S' shape suction side for flow precompression at transonic inlet Mach numbers. For high subsonic inlet flows and high incidence angles (about $10^{o}$), the airfoil suffers a severe flow separation on the first half of the suction side. The initial steady-state investigations showed significant flow pattern variations among the cascade blades. Therefore, the work first focused on improving the steady-state periodicity of the cascade flow pattern. Recently, NASA GRC extensively modernized and refurbished the facility. The boundary layer bleed system was completely overhauled, and it is now possible to monitor its adjustment on line. However, these changes did not improve the flow uniformity and periodicity significantly, particularly for high subsonic and transonic Mach number flows.

The CFD analysis of the blade cascade showed that for the incidence of $10^{o}$, the cascade turns the flow for only about $4^{o}$ due to flow separation on the front portion of the blade suction side. The cascade facility, however, was originally set for flow turning of $10^{o}$ for the same incidence angle. This resulted in tunnel wall interference with the cascade flow that significantly affected the flow pattern, which explains the tunnel-bleed system inefficiency in improving the flow pattern. The cascade setting was rearranged for a smaller turning angle of $4^{o}$, which noticeably improved the pressure uniformity upstream and 'far' down stream of the cascade, but the flow periodicity in the right half of the cascade was still not good enough. Decreasing the tunnel turning angle caused a mismatch between the tunnel wall and the suction side of the last blade on the cascade right-hand side. Consequently, the end blade suffers a massive flow separation over the entire suction surface that affects the flow pattern of the adjacent blades.

Based on the previous experimental results and CFD analysis, a solution was found for shaping the tunnel wall that should prevent flow separation on the last blade and its effect on the cascade flow periodicity. The evaluation work is still in progress, but the results so far demonstrate the careful and meticulous approach to secure the highest possible reliability and repeatability of experimental data acquired in this facility.

**Participating Organizations:** NASA Glenn, Pratt & Whitney

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## 5.2.4 F109 Unsteady Stator Loading
***FY 95-99***

**Background:** The objectives of the work are to collect, reduce, and analyze unsteady velocity data from the Honeywell F109 turbofan engine at the Air Force Academy in Colorado Springs, Colorado (Fig. 35). The specific areas of interest were upstream of the fan, or "fan forward" region, and upstream and downstream of the stators located behind the fan. All velocity data was taken with a two-wire hot wire, which was phase locked with the rotor.

The conclusions drawn from the analysis of the "fan forward" data are that relatively large, unsteady, velocity disturbances are present in the flow approaching the fan. The unsteady potential field generated by the individual fan blades as they rotate causes these disturbances. The disturbances radiate at acoustic speed into the oncoming flow field in a spiraling helical pattern. The amplitude of the measured unsteady velocity is as high as 50% of the mean-axial-velocity very close to the fan, and is as low as 2-5% of the mean-axial-velocity at 1.0 fan chord (2.61 in) upstream of the fan. The data collected downstream of the fan indicates the presence of a convectively-propagating wake disturbance superimposed on an acoustically-propagating potential disturbance. These results confirm that it was the combination of these two disturbances that produced the unsteady pressure response measured on the surface of the stators in a previous effort.

**Recent Progress:** Current efforts are focused on the development of a small probe to measure the unsteady surface pressure distribution produced by the large-amplitude velocity fluctuations upstream of the fan. A test probe has been fabricated by Notre Dame for use in their cascade wind tunnel. This probe is scheduled to be tested this summer (1999). Based on the results of this testing, a probe will be designed and built for use in the F109 engine at the Air Force Academy. F109 engine testing is planned for the Aug 99 - May 00 timeframe.

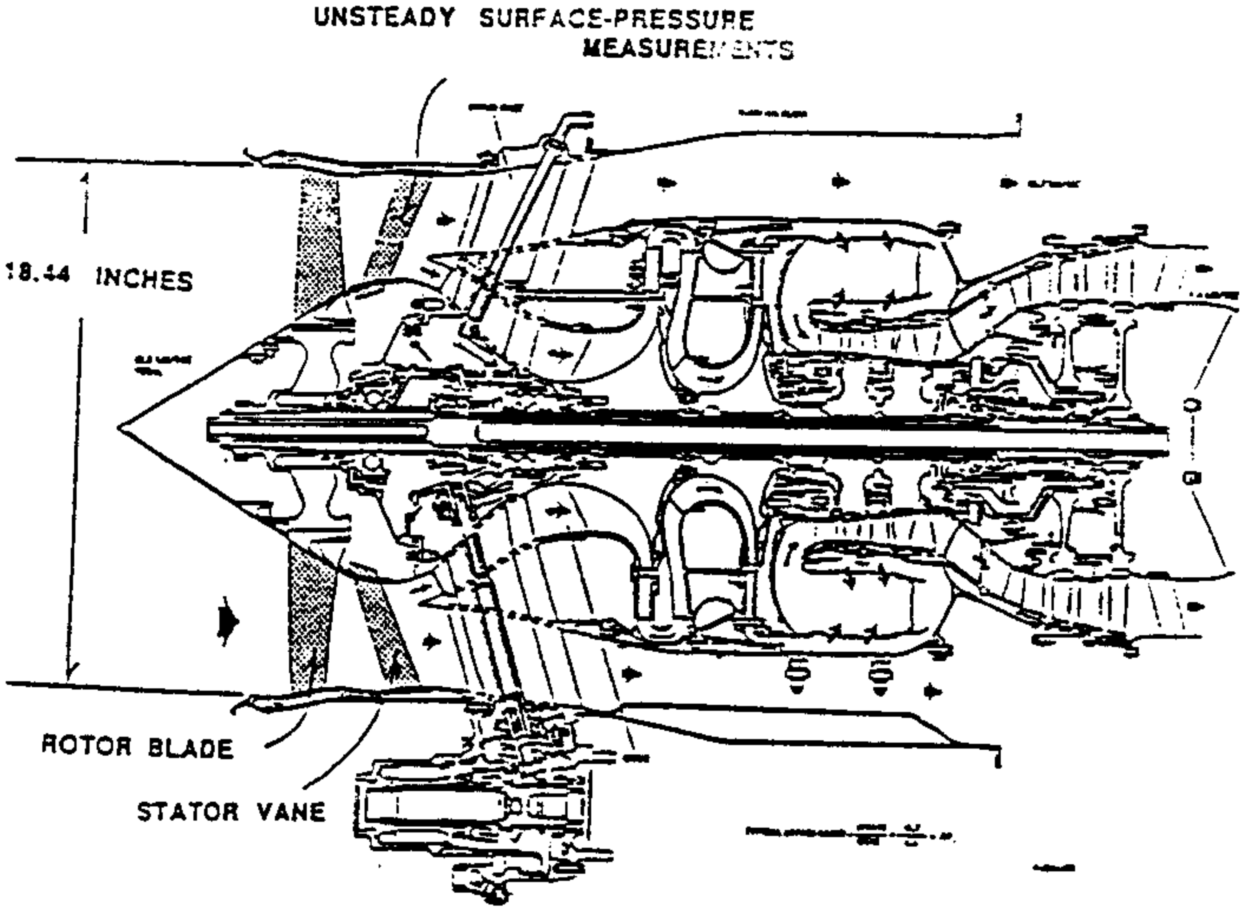


**FIGURE 35.** Schematic of F109 Engine Showing Location of Pressure-Instrumented Stators

**<u>Participating Organizations</u>:** U.S. Air Force Academy, Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), University of Notre Dame

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### 5.2.5 Fluid-Structure Interaction (Fans)

*FY 96-01*

**Background:** The objective of this effort is to develop the technology needed to accurately predict significant blade row forced response in a multistage environment. Specific objectives include: (1) developing a benchmark standard multistage transonic research compressor; (2) developing a quantitative understanding and predictive capability for multistage blade row forced response; (3) addressing the inherently small damping of complex higher-order modes; (4) investigating techniques to control the flow-induced vibrations; and (5) developing a better understanding of robustness, nonlinearities, and fluid-structure interactions.

The aerodynamic design of the advanced design inlet guide vane (IGV), rotor, and downstream stator rows has been completed. The IGV, rotor, and stator vanes have been fabricated, with the IGV and stators instrumented. Unsteady aerodynamic interactions between the IGV and rotor of an advanced design transonic multistage compressor have been experimentally investigated, with the rotor-generated forcing function and resultant IGV response measured and analyzed at both design and part-speed operating conditions. The effect of aerodynamic blade-to-blade variability on the wake-generated forcing function and its impact on the downstream vane row unsteady aerodynamic response has been experimentally investigated in a high-speed fan stage at both design and off-design rotor operating conditions.

**Recent Progress:** Investigations into multistage unsteady aerodynamic analysis have been initiated. The following observations have been made. First, the aerodynamic damping of a blade row in a multistage machine can be significantly different from that predicted using an isolated blade row model. This is important since most current models do not account for multistage effects, and thus may significantly over or under predict aerodynamic damping. Second, it may be possible to use the multistage influence on aerodynamic damping to reduce aeroelastic vibrations. For example, the designer may be able to alter the spacing between blade rows to increase aerodynamic damping. Third, using the present method, a good estimate of the aerodynamic damping can be obtained using just a few of the many possible spinning modes. This is fortunate since computational cost grows with the number of spinning modes retained in the model. Finally, the present coupled mode analysis is computationally very efficient, two or more orders of magnitude more efficient than time-marching simulations. The implication is that such multistage computations will be efficient enough for use in design, eliminating potential aeromechanics problems not predicted using isolated blade row models.

Research under this initiative will include continued analytical development of multistage effects. Continued experimental research includes the measurement of the stator response and measurements utilizing the new rotor in the test rig. With the new rotor installed, investigations into rotor-stator and rotor-IGV interactions will be performed, and airfoil response for each blade row will be measured.

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## 5.2.6 Experimental Study of Forced Response in Turbine
*FY 97-00*

**Background:** The purpose of this project is to develop an understanding of the forcing function, aerodynamic damping, and structural damping at actual engine conditions for high-frequency vibration of turbine blades. An actual Honeywell TFE731-2 high-pressure turbine will be studied in the Gas Turbine Laboratory at Ohio State University. The original blades, which had a severe high-frequency vibration problem, will be evaluated in conjunction with two other turbine designs. For each configuration, unsteady surface pressures and blade response will be measured at actual operating conditions. The result of this research will be a database that can be used to validate future prediction codes.

**Recent Progress:** The UNSFLO Computational Fluid Dynamics (CFD) simulation of turbine stage and the ANSYS finite element method (FEM) analysis of blade natural frequency have been completed. Because of reduction in funding, the test plan had to be scaled down, and actual engine conditions were replaced by corrected conditions. All the tests were completed successfully, and the data analysis is in progress. The period of performance on the contract was extended to February 2000.

**Participating Organizations:** GUIde, NASA

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# 5.3 Validation of Analytical Models

The objective of the following projects is to utilize existing experimental data to validate models for improved forced response prediction.

## 5.3.1 Evaluation of Current State-of-the-Art Unsteady Aerodynamic Models for the Prediction of Flutter & Forced Vibration Response

***FY 97***

**Background:** The objective of this project was to evaluate the capabilities of current state-of-the-art unsteady aerodynamic models that attempt to predict the gust and oscillating airfoil response of compressor and turbine airfoils over a range of realistic frequencies and loading levels. Additionally, the effect of the aerodynamic forcing function on gust response, and the effects of three-dimensional flow on airfoil oscillation will be investigated. Codes utilized were primarily NASA Glenn codes, such as Nphase, Sflow, Linflow, and Linflux.

**Final Results:** This program was terminated when the principal investigator left academia. However, an initial investigation into the capabilities of two state-of-the-art computational models was performed. The unsteady pressure and first harmonic unsteady surface pressure coefficients determined from experiments were correlated with the predictions. The experimental data used was for the NASA/PW fourth standard configuration. Viscous and inviscid flow solutions were generated.

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## 5.3.2 Evaluation of State-of-the-Art Unsteady Aerodynamic Models

***FY 99-02***

**Background:** The objective of this project is to evaluate the capabilities of current state-of-the-art unsteady aerodynamic models that attempt to predict the gust and oscillating airfoil response of compressor and turbine airfoils over a range of realistic frequencies and loading levels. Additionally, the effect of the aerodynamic forcing function on gust response and the effects of three-dimensional flow on airfoil oscillation will be investigated. Codes currently under evaluation are TURBO, ADPAC, and 3DVBI.

**Recent Progress:** This effort officially started in March 99. Research utilizing the 3DVBI and ADPAC codes has been initiated. Efforts utilizing 3DVBI are being lead by WSU, in conjunction with AFRL's CARL facility. Comparisons of the code's prediction capability with experimental data from the CARL facility are being performed. In general, the 3DVBI code has compared quite favorably with the experimental results in the core region of the flow, but the endwall regions need additional investigating before conclusions can be made.

Similar comparisons are being initiated with the NASA ADPAC code through the University of Dayton. Test cases have been run, and steady IGV comparisons to the CARL data have been initiated. The third code under this effort is TURBO. The lead for this effort is the University of Cincinnati. Similar comparisons are planned, but have not been initiated.

**Participating Organizations:** Air Force Research Laboratory (AFRL), Wright State University

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## 5.3.3 Forced Response Prediction System (Fans)

***FY 95-01***

**Background:** The objective of this project is to develop and validate NASA's new Forced Response Prediction System design tools. Three codes are being developed for forced response predictions: FREPS, FREED, and TURBO with aeroelastic capability. FREPS uses two-dimensional linearized potential unsteady aerodynamics and is the fastest running of the codes. The development and validation of FREPS is complete and is being followed by the development of FREED. FREED uses steady Euler aerodynamics from the TURBO code, and linearized three-dimensional unsteady Euler aerodynamics from LINFLUX. LINFLUX is a turbomachinery code developed under a contract from NASA Glenn Research Center (formerly Lewis Research Center). The linearized code FREED and the fully non-linear code TURBO (with aeroelastic capability) are complimentary. Both codes are based on the same algorithm, but each provides a different level of physics modeling and has different computational requirements. The TURBO code, described elsewhere in this report, is the longest running of the three codes. The structural dynamic model of the blade for the three codes is based on a normal mode representation.

**Recent Progress:** Initial work has focused on installing the LINFLUX code on different computer workstations, and exercising the code to gain familiarity with its operation. An interface code is required to convert the steady TURBO solutions for use with LINFLUX. The interface code is being updated to work with the latest version of TURBO. In addition, the interface code is being modified to work on the Cray C-90, where the steady TURBO solutions are currently being run. The most recent version of LINFLUX includes the capability to model incoming vortical gusts; this capability was not present in prior versions of the code. Future plans include improvement of the steady solver to obtain faster convergence and to obtain solutions with reduced numerical losses. In addition, the FREED code will be validated using configurations that are of current interest to industry.

**Participating Organizations:** NASA

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## 5.3.4 Aeromechanical Design System Validation

***FY 96-00***

**Recent Progress:** The response of an existing rotor has been measured, and a full rotor finite element method (FEM) analysis has been performed. Next, the FEM code will be coupled with a model of the inlet flow field, and the resulting vibratory stresses will be predicted. The predictions will be compared with bench data, and recommendations for additional code development will be made.

**Participating Organizations:** Air Force Research Laboratory (AFRL), Pratt & Whitney

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## 5.3.5 Probabilistic Structural Analysis Methods

***99-01***

**Background:** The NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) probabilistic structural analysis computer program combines state-of-the-art probabilistic algorithms with general purpose structural analysis methods to compute the probabilistic response and the reliability of engineering structures. Uncertainty in loading, material properties, geometry, boundary conditions, and initial conditions can be simulated. The structural analysis methods include nonlinear finite element methods, boundary element methods, and user-written subroutines. Several probabilistic algorithms are available, such as the advanced mean value method and the adaptive importance sampling.

**Recent Progress:** Recently, NESSUS was augmented with the Heat Transfer analysis capability of the EPM backbone computer code CSTEM (Coupled Structural, Thermal, and Electro Magnetic Tailoring)—resulting in NESTEM code. NESTEM can now analyze/assess the complex thermal environment with uncertainties and its effects on the overall component response. Typical output of the code is probabilistic stress distributions at hot spots, probabilistic vibration frequencies and buckling loads. This information allows the designer to make more informed judgments regarding the preliminary design of the components without resorting to overly conservative deterministic approaches with ad-hoc knock-down factors. The information also permits more accurate calculation of the reliability and life of such components. The code also provides information on sensitivities of the various uncertainties and ranks them in the order of importance as a by-product.

Recently, the NESTEM code was enhanced to include the capability to define harmonic excitation parameters. The enhanced capability allows the analysis of three types of harmonic excitations: harmonic nodal forces, harmonic-based accelerations, and harmonic nodal pressures. These improvements will allow us to address some high cycle fatigue (HCF) problems. Furthermore, there is a need to address creep and fatigue-related models as well as lifing-related problems. These methodologies will be ultimately used to computationally simulate and probabilistically evaluate the Department of Defense's disk model, and the methodologies will be verified using the experimental test data from Pratt & Whitney.

**Participating Organizations:** Modern Technologies Corporation

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## 5.4 Conclusion

The Forced Response Action Team has successfully developed models to understand and predict friction and mistuning in gas turbine engine disks. Two models have been transitioned to industry and used to investigate field problems on both the F100 and F110. "BDAMPER," a code developed through the GUIde Forced Response Consortium, is successfully predicting resonant responses of frictionally constrained blades. Applied to the F100 3rd fan blade design, its use has resulted in a 62% reduction in unscheduled maintenance man-hours. "REDUCE," a bladed disk mistuning code, is being utilized by several turbine engine companies, and is successfully predicting response trends in bladed disk assemblies. Additionally, the government and industry are jointly pursuing new codes for flutter and resonant stress prediction. Many efforts have been coordinated and developed through the GUIde consortium of government, engine contractors, and universities, with validation performed through basic research, component rig testing, and production engine operation.

# 6.0 PASSIVE DAMPING TECHNOLOGY

**BACKGROUND**

The Passive Damping Technology Action Team (Damping AT) has the responsibility of fostering collaboration between individual HCF passive damping efforts with the overall goal of damping component resonant stress by 60% for fans and 25% for turbines. The Damping AT provides technical coordination and communication between active participants involved in HCF passive damping technology. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair and selected Damping AT members meet as required (estimated semi-annually) to review damping activities, develop specific goals for passive damping programs, and coordinate with the TPT and IAP. The Chair (or Co-Chair) of the Damping AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in damping technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

**ACTION TEAM CHAIRS**

**The following appointments are effective as of 1 Jan 2000.**

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**To the outgoing chairs, Don Zabierek and Dave Barrett, an enthusiastic "Thank you" for your years of outstanding service to the Passive Damping Action Team and to the National High Cycle Fatigue Science and Technology Program, and best wishes in your future endeavors.**

**INTRODUCTION:** The following pages contain tables, schedules, backgrounds, and summaries of the recent progress of current and planned tasks managed by this action team.

# Passive Damping Schedule

**Current & Planned Efforts**

***6.1 Identification/Characterization of Damping Techniques***

6.1.1 Air Force In-House Damping Investigations

6.1.2 Centrifugally Loaded Viscoelastic Material Characterization Testing

6.1.3 Mechanical Damping Concepts

6.1.4 Damping for Extreme Environments

6.1.5 Centrifugally Loaded Particle Damping

***6.2 Modeling and Incorporation of Damping in Components***

6.2.1 Advanced Damping Concepts for Reduced HCF

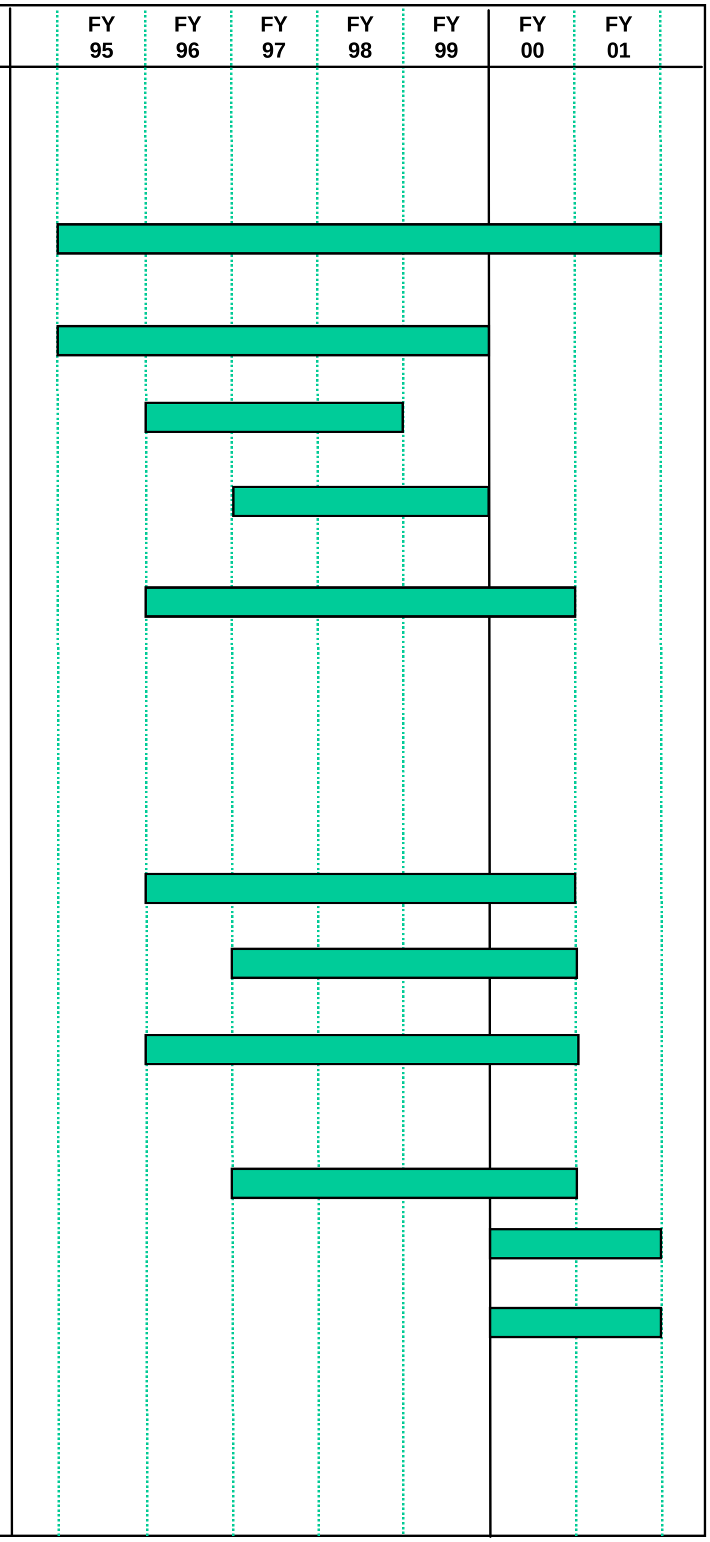
6.2.2 Damping Systems for IHPTET

6.2.3 Evaluation of Reinforced Swept Airfoils / Internal Dampers

6.2.4 Damping for Turbines

6.2.5 Dual Use Program

6.2.6 Transition of Damping Technology to Counterrotating LPT Blades



# 6.1 *Identification and Characterization of Damping Techniques*

Four types of passive damping systems, judged to have a reasonable chance of effectively damping rotating engine components, are being investigated: (1) friction damping systems, which have been used in platform and shroud applications and now show promise as devices internal to blades, (2) viscoelastic material systems, which have mature design optimization procedures and are now being designed to function under high centrifugal loads, (3) particle damping systems, which have the potential of providing damping independent of temperature, but require a lot of effort in characterization and design optimization, and (4) powder damping systems, which are an extension of the tribology of dry film lubricants, have temperature independent damping, and require the most work in the development of acceptable systems.

## 6.1.1 Mechanical Damping Concepts

***FY 95-01***

**Recent Progress:** For the past year, researchers at NASA Glenn Research Center (GRC) have been investigating several damping methods for rotating blades. Oral Mehmed, NASA Senior Research Engineer, and Dr. Kirsten Duffy of the Ohio Aerospace Institute have been working with Dr. Ronald Bagley of the University of Texas at San Antonio to study the self-tuning impact damper. Oral Mehmed has also been working with Dr. John Kosmatka at the University of California at San Diego to investigate viscoelastic damping in composite blades.

A self-tuning impact damper was tested in 1999 that significantly reduced resonant vibrations at engine order crossings. The frequency of motion of the damper is proportional to the rotor spin rate, causing it to function along an engine order line. Tests were performed in flat aluminum plates at up to 2600 g's in the NASA Dynamic Spin Facility (Fig. 36). Damping of up to 2.0% critical was obtained at the engine order crossings over a baseline damping of about 0.2%. A follow-up test is being planned for late 1999 to test these dampers at up to 10,000 g's in the same flat plates. In order to show the feasibility of damping for very thin blades, another test will be performed this winter on a miniaturized self-tuning damper. Here, very small impactors will be distributed over an area of a plate. A future goal is to demonstrate the self-tuning impact damper in a blade configuration.

Research is also being conducted in the area of integrally damped composite blades. The objective of this research is to develop technology to passively damp blades made of composite material by designing and fabricating the blades with viscoelastic material built in. Earlier analytical and experimental research with spinning composite plates showed that the concept works and that the damping benefits are significant. New research in 1999 is aimed at demonstrating an integral damping design for a scale model of a modern composite fan blade. The damping design is focused on maximizing the blade damping for a specific rotating speed range and mode, while maintaining the initial structural static and dynamic properties. These scale model fan blades have been fabricated, and spinning structural characterization is planned at the NASA Dynamic Spin Facility in late 1999 or early 2000.

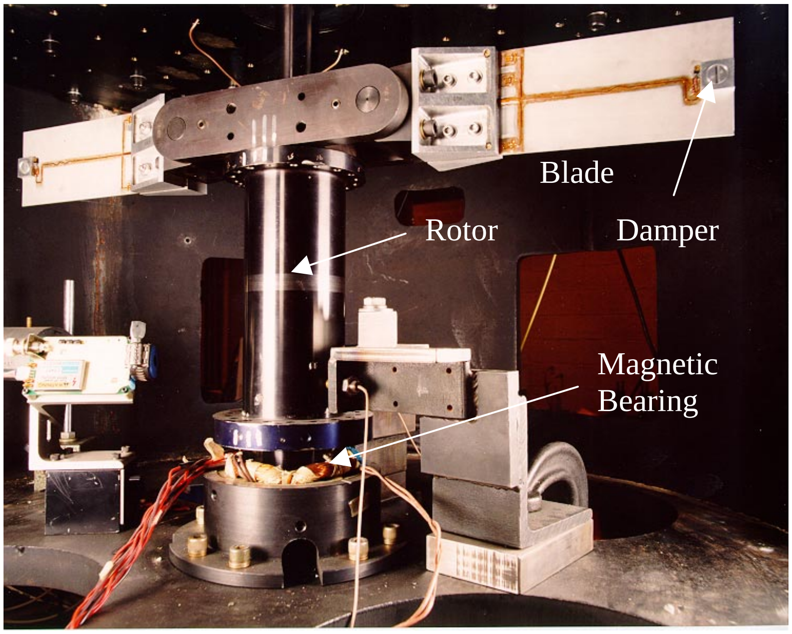



**FIGURE 36.** Dynamic Spin Facility, NASA Glenn Research Center

**Participating Organizations:** NASA, University of California, Ohio Aerospace Institute, University of Texas at San Antonio

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## 6.1.2 Air Force In-House Damping Investigations
***FY 95-99***

**Background:** The objective of this task in FY99 was to investigate the use of piezoelectric actuators to increase coupling in an integrally bladed rotor. Mistuning can cause blades to experience much higher operating stresses than would occur in a perfectly tuned system. Increasing blade-to-blade coupling can reduce this non-uniformity. In this task, piezoelectric actuators were attached to an integrally bladed disk and modal tests were conducted to access the amount of additional coupling provided by the actuators.

Ideally, a bladed disk is a periodic system with the substructures and blades all having identical natural frequencies. However, there will be slight variations in the blades. These variations mistune the individual blade natural frequencies and affect the system as a whole. The dynamic behavior of the bladed disk depends on the degree of mistuning and coupling that exists in the system. When the amount of mistuning is small or the coupling is strong, the mode shapes are said to be extended, i.e., they are regular patterns that involve all the blades. As the mistuning is increased or the coupling weakens, the mode shapes tend to become irregular, with amplitude concentrated in a few blades.

Piezoelectric strain actuators have been used to add damping to structures. These actuators have the potential to augment the coupling of engine blades. As a blade deforms during vibration, an electrical charge is induced in a strain actuator located in an area of high modal strain on the blade. The induced charge can then be transferred through an electric circuit to an actuator on another blade causing the second blade to also deform. This sharing of energy between blades is similar to connecting the two blades with a mechanical spring.

**Final Results:** Experiments were conducted on a model jet engine fan to evaluate the effects of piezoelectric coupling of blades on mode shapes. The model fan, shown in Figure 37, was used as the test article in this study. It is a variant of a model developed under a previous study and is representative of a modern fighter engine's first-stage fan. The model fan had an overall diameter of 18 inches. The blades and hub were fabricated from low-alloy steel. The blades were soft soldered into slots in the hub at a 45° angle to the fan's axis of rotation. The blades were 6 inches long, 4.5 inches wide and 0.063 inches thick. The cylindrical hub had a diameter of 6 inches. The hub wall thickness was 0.325 inches.

The 2-stripe family of modes was chosen for study. Piezoelectric strain actuators were placed on the blades in an area of high modal strain for the local 2-stripe mode shape. Each piezoelectric strain actuator was a sheet of G-1195 lead zirconate titanate (PZT). The dimensions of each actuator were 1.5 inches by 1.5 inches by 10 mils thick. Actuators were bonded to the front and back of each blade. The location of the front actuators are apparent in Figure 37, the back actuators are at the same locations on the other side of the blades. The negative side of each actuator is electrically grounded to the fan using conductive adhesive.

The model fan was inherently mistuned due to small variations in the blades. The natural frequencies of the individual blades (with all sensors, actuators, and wiring in place) were measured to quantify the mistuning. The frequency of each blade was measured, one at a time, by adding small tip masses to the other blades to "detune" them and localize the mode shape to the blade of interest. The average natural frequency measured was 789.4 Hz. The frequency spread from the highest to the lowest frequency blade was 10 Hz or 1.3% of the average frequency.

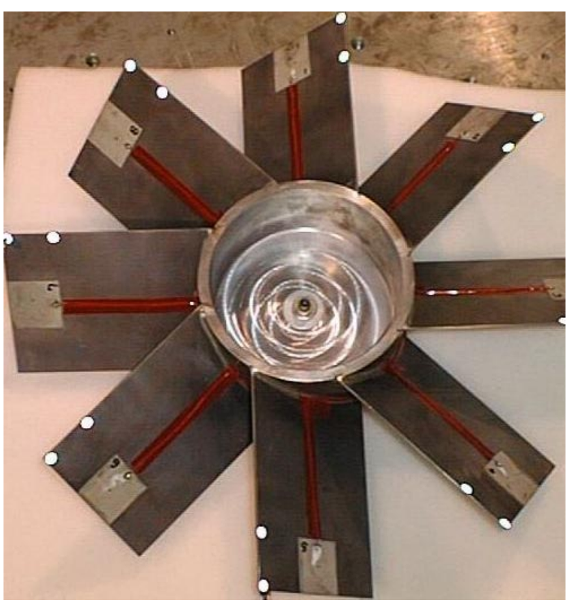

**FIGURE 37.** Model Fan Test Article

In addition to studying the effects of coupling on the mistuned model, it was desired to test the model in a nearly-tuned configuration. To tune the model, the natural frequencies were altered through the addition of small masses to each blade. A trial and error procedure was used to decrease the frequency spread from 10 Hz to 0.5 Hz. The spread is only 0.06% of the new average frequency of 783.7 Hz. This configuration will be referred to as the "tuned" fan.

The piezoelectric actuators can be electrically connected to achieve many coupling arrangements. In previous work with an analytical model, a single coupling spring was used to couple adjacent blades. The piezoelectric actuators on the model fan were connected to mimic this model. Each front piezoelectric actuator was connected to the back actuator of the next blade as depicted in Figure 38.

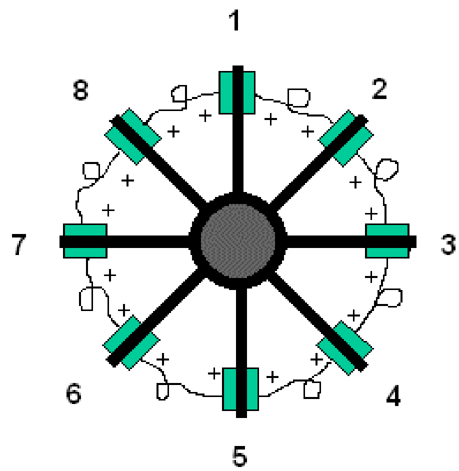


**FIGURE 38.** The Electrical Connections between Piezoelectric Actuators

The mode shapes for a perfectly tuned system, often called the extended mode shapes, are shown in Figure 39. Extended mode shapes can also occur with a mistuned system if the coupling is strong enough. Achieving extended mode shapes and therefore tuned forced response behavior was the goal of the coupling experiments. For the mode shapes depicted in Figure 39, the length of the radial line in the 12 o'clock position represents the relative modal amplitude of blade 1. The amplitudes of blades 2-8 are represented by the other seven radial lines (numbered clockwise). Solid lines represent blades vibrating in-phase and dotted lines represent blades vibrating out-of-phase. The orientations of the three orthogonal pairs of modes (2-3, 4-5, and 6-7) are arbitrary.

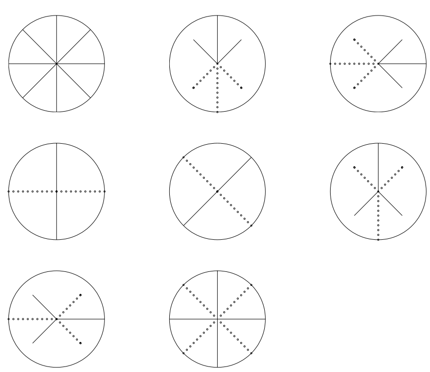

**FIGURE 39.** Extended Mode Shapes for Eight Blades

Two tests were conducted on the model fan in the mistuned configuration. In the first case, the piezoelectric couplers were not connected and left in the open electrical boundary condition. This case will be referred to as the mistuned, uncoupled case. In the second case, the couplers were connected as shown in Figure 38. This case will be referred to as the mistuned, coupled case.

Modal results for the mistuned, uncoupled case are shown in Figure 40. The mode shapes are generally localized. Modes 1-3, 7, and 8 are mostly localized to a single blade. The other three modes, 4-6, primarily involve blades 2, 3, and 8. These results are readily inferred from the individual blade frequencies. That is, the tendency for two blades to participate in the same mode is directly related to the difference in their individual frequencies.

It is evident from Figure 40 that inter-blade coupling for the 2-stripe mode family is very weak. As discussed previously, extended modes (tuned behavior) can result from either of two conditions—coincident frequencies or large inter-blade coupling. The mode shapes indicate very weak coupling, since the blades that do not have nearly-coincident frequencies are mostly localized. This behavior is to be expected from the 2-stripe mode family since the local mode shape has very little strain energy near the blade root and thus has poor means for coupling through the hub. Therefore, a large increase in coupling of the 2-stripe family is needed to achieve extended behavior.

Modal results for the mistuned, coupled case are shown in Figure 41. A moderate increase in coupling is evident. Generally speaking, each mode shows increased participation from all the blades. The piezoelectric coupling has caused blades 4 and 7, which were previously localized, to strongly interact with blades 2, 3, and 8. Modes 1, 7, and 8 are still mostly localized to blades 6, 5, and 1, respectively, but there is some small participation of adjacent blades. Although the overall coupling has improved, the resulting mode shapes are far from the extended case. The added coupling from the piezoelectric actuators is too weak to have the desired results.

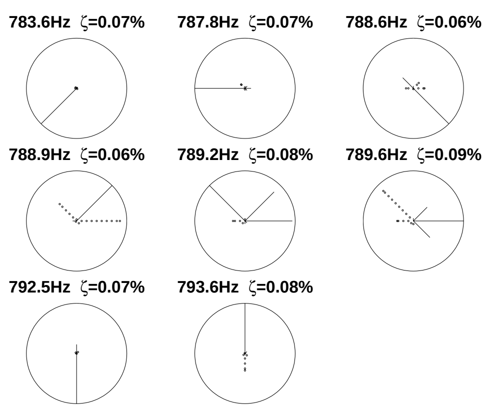


**FIGURE 40.** Mode Shapes for the Mistuned, Uncoupled Case

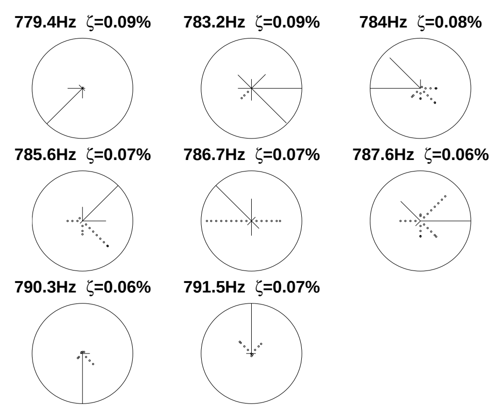


**FIGURE 41.** Mode Shapes for the Mistuned, Coupled Case

After it was determined that the piezoelectric coupling was not strong enough to achieve extended modes in the mistuned fan, it was decided to see if the coupling could force extended modes in a nearly tuned system. The blades were “tuned” as described previously, and modal tests were conducted for two coupling cases. In the first case, the piezoelectric couplers were not connected and left in the open electrical boundary condition. This case will be referred to as the tuned, uncoupled case (Fig. 42). In the second case, referred to as the tuned, coupled case, the couplers were connected as shown in Figure 43.

The modal results for the tuned, uncoupled case are shown in Figure 42. There is significant participation of most blades in most modes, but only three of the mode shapes (5, 7, and 8) appear to approach the extended mode shapes.

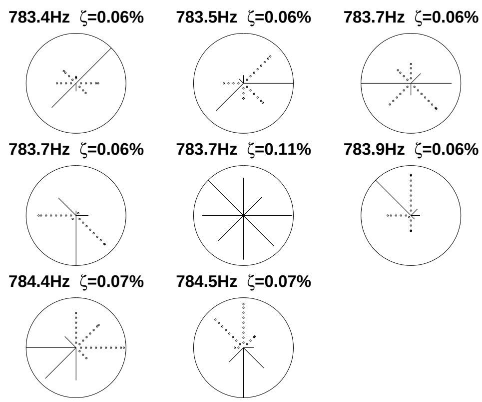


**FIGURE 42.** Mode Shapes for the Tuned, Uncoupled Case

The modal results for the tuned, coupled case are shown in Figure 43. All the mode shapes closely approximate the extended mode shapes and are in the proper order. With the system nearly tuned, the added coupling from the piezoelectric actuators is sufficient to cause the extended shapes to appear.

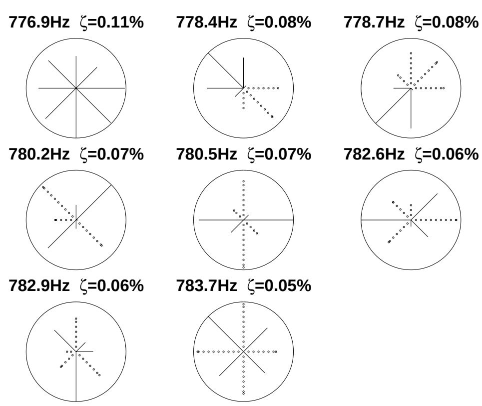


**FIGURE 43.** Mode Shapes for the Tuned, Coupled Case

The results indicate that the piezoelectric actuators did improve blade-to-blade coupling, but the improvement was weaker than hoped. Only the tuned, coupled configuration was able to achieve the desired extended mode shapes. The disappointing performance of the piezoelectric couplers can be qualitatively attributed to their lack of efficiency. Even though the size and location of each actuator captures a significant portion of the strain in the 2-stripe mode of a blade, conversion of this strain to electrical energy is limited by the inefficiency of the piezoelectric actuator.

The piezoelectric actuators would be much more beneficial at reducing the blade stresses in a mistuned system if they were used to add damping instead of increasing coupling. Results in the literature indicate that the damping of a very lightly damped engine blade could be easily increased by an order of magnitude with a tuned piezoelectric absorber. Increasing the damping by an order of magnitude reduces blade stresses by the same amount. This stress reduction is much more than could be expected from the elimination of rogue behavior in a mistuned system by increasing the blade-to-blade coupling.

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## 6.1.3 Centrifugally Loaded Viscoelastic Material Characterization Testing

***FY 96-98***

CSA Engineering was tasked to characterize the behavior of viscoelastic material under centrifugal loads. While a great deal of work was done characterizing and measuring the Poisson's ratio of representative viscoelastic material in the laboratory environment, only the results of exposing viscoelastic material to centrifugal loads in a spin test are discussed here. Two types of blades were spun. The purpose of the first type of blade (shown in Fig. 44) was solely to study the effect of quasi-static centrifugal loading on viscoelastic material. The material, cast in a pocket, was subjected to up to 25,000 g's. The predicted strain over the pocket compared well with measured strain.

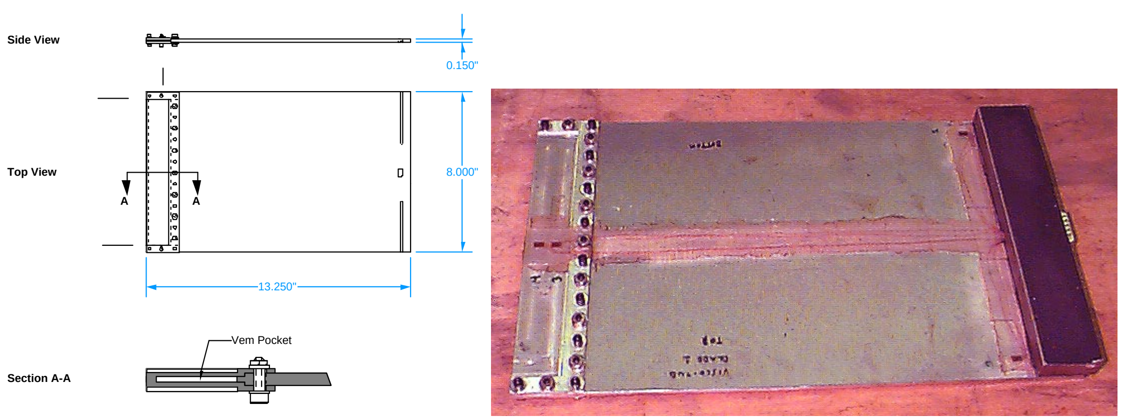


**FIGURE 44.** Viscoelastic Tub Blade Hardware

The second type of blade was designed to study the issues involved with damping fan blades cost effectively. The developed blade, shown in Figure 45, had a 1.5 aspect ratio. The blade consisted of two face sheets, the thicker of which had two 0.050-inch deep cavities that could be left empty or filled with viscoelastics. The sheets were held together with bolts and epoxy. The blade was instrumented with strain gages and piezoelectric patch (PZT) actuators.

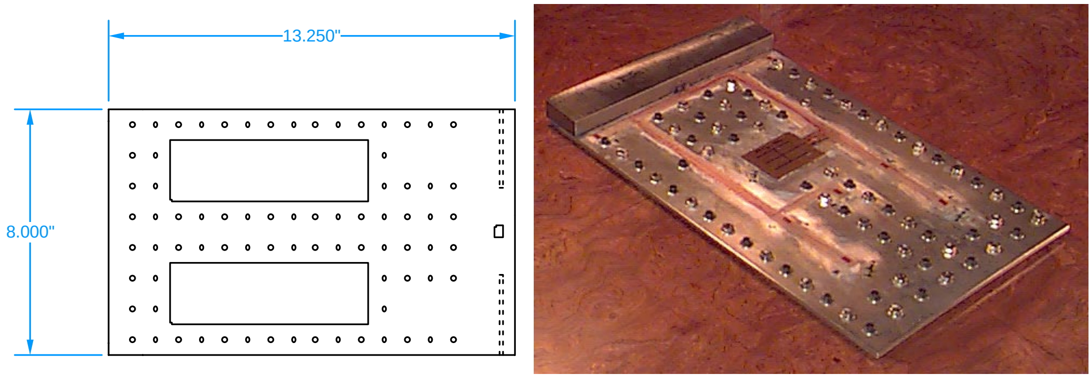


**FIGURE 45.** Damping Study Blade

The spun blade had one cavity filled with viscoelastic material and one empty cavity. This allowed further study of the effects of quasi-static stress on face sheets containing viscoelastics. A comparison of measured vs. predicted strain is shown in Figure 46. The measured strains for the full cavity are consistently higher than those for the empty one, as predicted. This blade was also exposed to 7,500 RPM, or the equivalent to 22,000 g's at the outmost location of the viscoelastic. The effectiveness of the damping design is seen in laboratory measurements comparing the damped blade and another completely empty but otherwise identical blade (see Fig. 47). The targeted higher-order modes, such as those near 400 and 700 Hz, were well damped. Damping would have been even more significant if both pockets had been full.

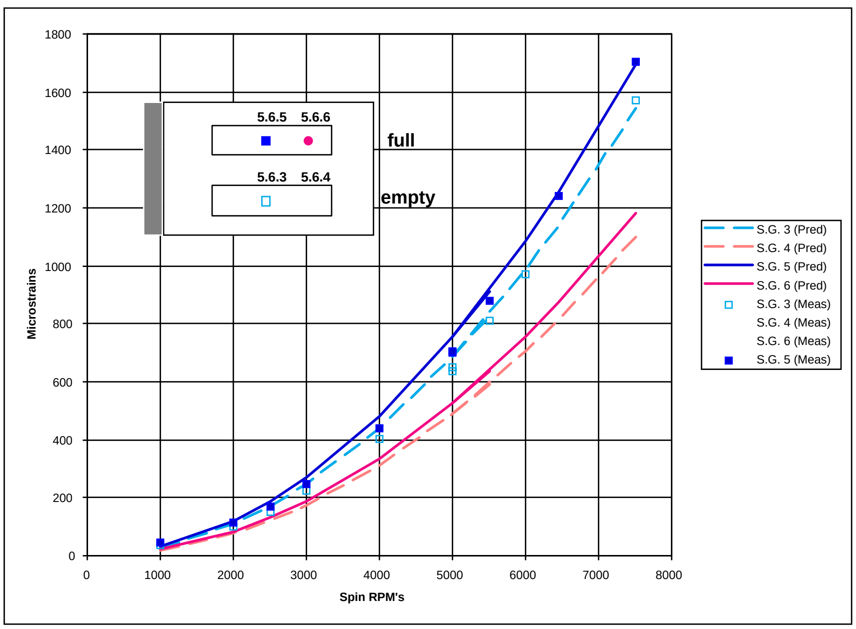


**FIGURE 46.** Comparison of Measured and Predicted Static Strain Over Cavity Locations for Various RPM Levels Where 7,500 RPM Corresponds to a Maximum of 22,000 g's

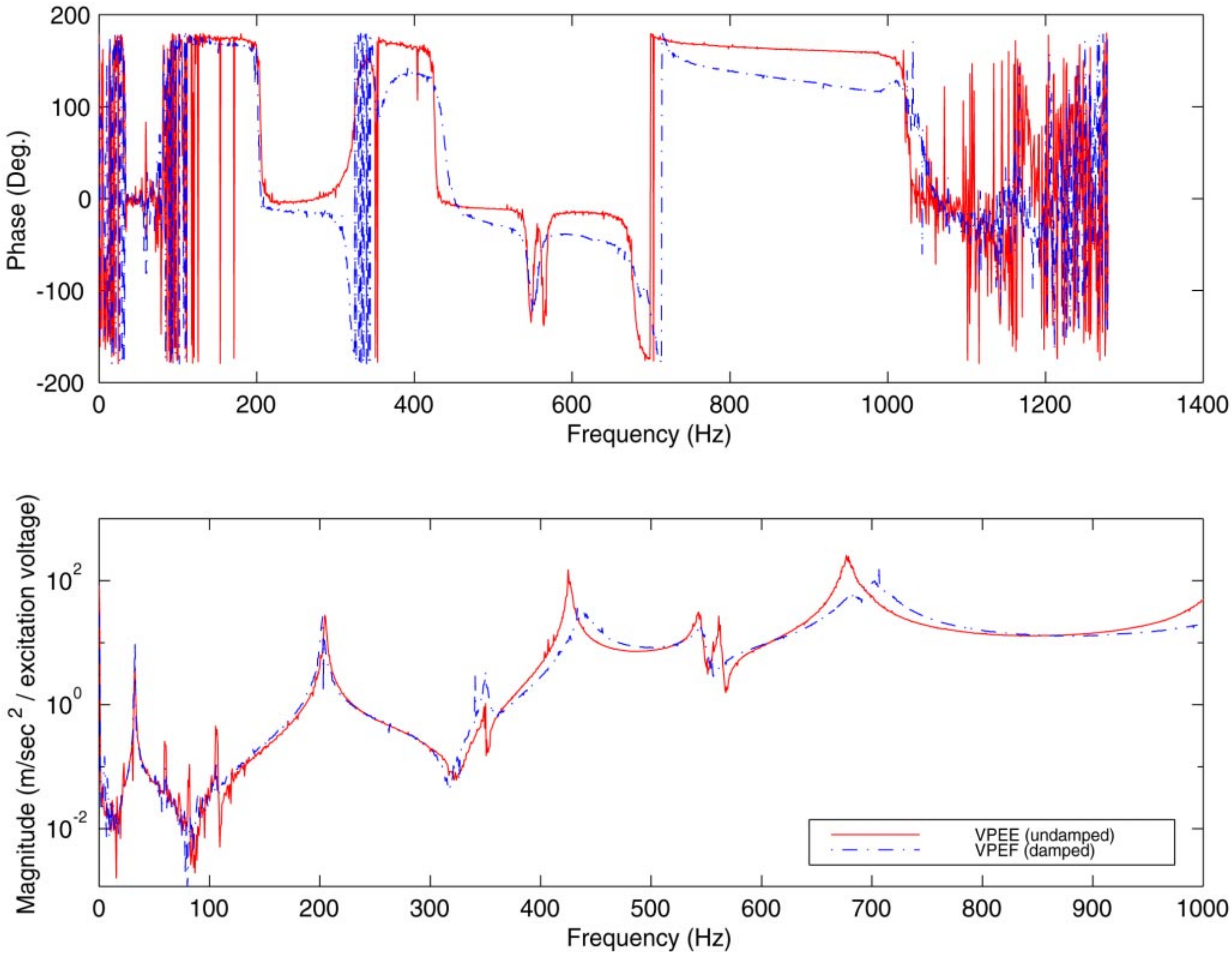


**FIGURE 47.** Comparison of Undamped and Damped Blade Response (One Pocket) to PZT Excitation in the Laboratory

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### 6.1.4 Damping for Extreme Environments

*FY 97-99*

**Background:** Multi-particle impact damping (MPID) consists of many small metallic or ceramic particles contained in a cavity that, when excited by vibrations, cause the base structural motion to be damped. Basically, the impact of particles on each other and on the cavity walls, friction between particles, and friction between particles and the cavity walls cause energy dissipation, which reduces the amplitude of the base structure vibration. Since the particles can be metallic or ceramic, they can be used at high temperatures, and since they can be designed to be temperature insensitive, the damping mechanisms are fairly temperature insensitive over wide temperature ranges.

**Recent Progress:** During the past year, much progress has been made in the analytical understanding of MPID. Early in the program, simple single degree-of-freedom (SDOF) models were developed. More sophisticated multiple degree-of-freedom (MDOF) models are currently being developed. The particle damper simulation code is based on X3D, an explicit finite element code typically used for impact analyses. The code contains various contact algorithms and bookkeeping routines and provides an appropriate framework for simulating particle damping through the use of the particle dynamics method. Force-displacement relations for both the normal and shear forces have been implemented. Preliminary simulation models are being developed, and the most appropriate method to estimate damping is being determined. Figure 48 shows simulated multiple-particle interactions.

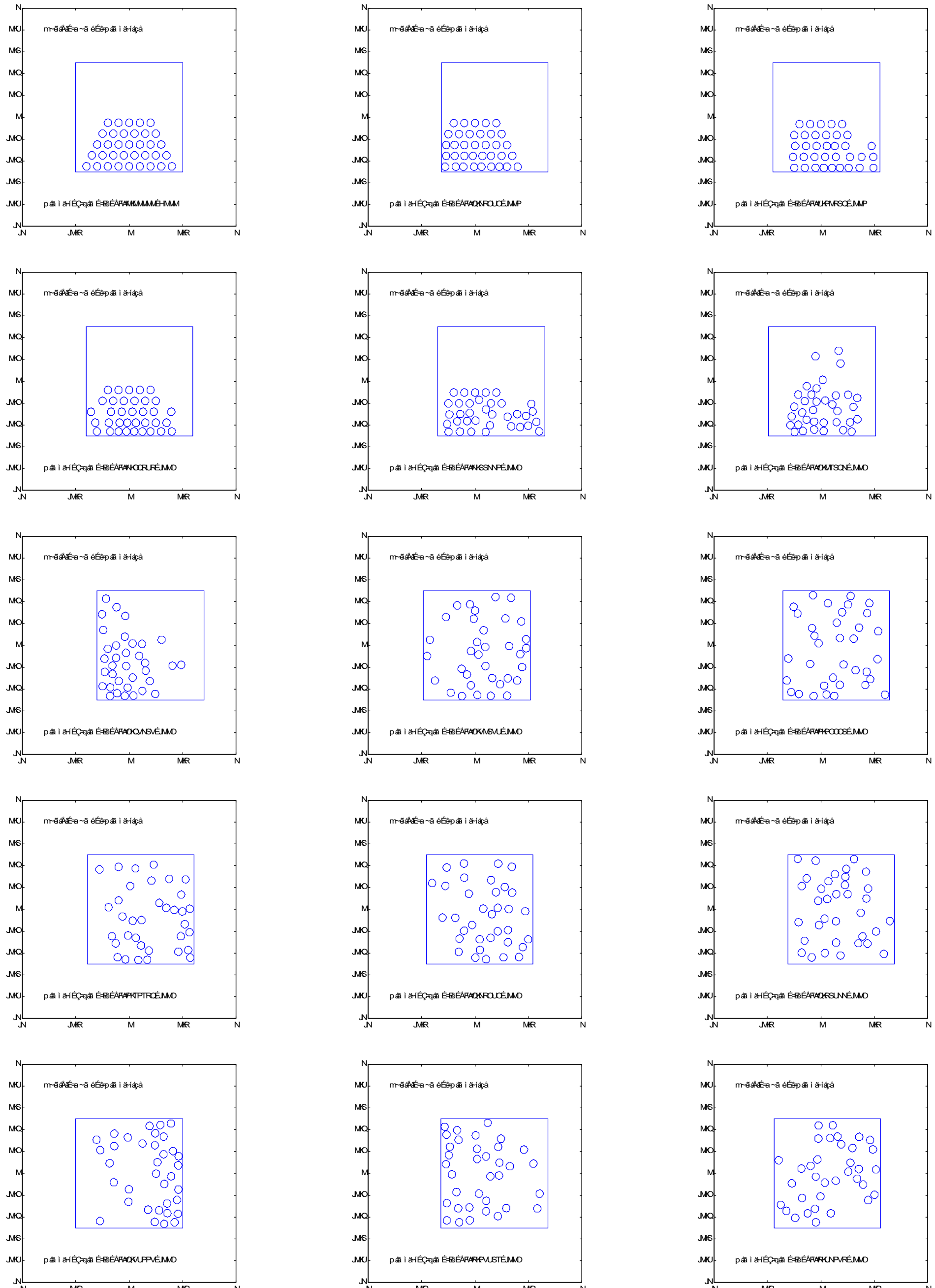

**FIGURE 48.** Selected Frames from Particle Damper Simulation

A high-temperature test system has been designed that is based on a cantilever beam. A freely-supported shaker is used to drive the beam. Response is transduced with an accelerometer. Since MPID is non-linear, sine-dwell testing is performed. A comparison of frequency response function (FRF) amplitude for damped and undamped systems at multiple excitation amplitudes is shown in Figure 49. Note that the test with a single particle shows high levels of damping until a “particle resonance” occurred. The second plot is much more representative of the amplitude reduction from multiple particles. Test data is currently being cataloged and compared to analytic predictions. High-temperature test articles with cavities of various sizes are shown in Figure 50.

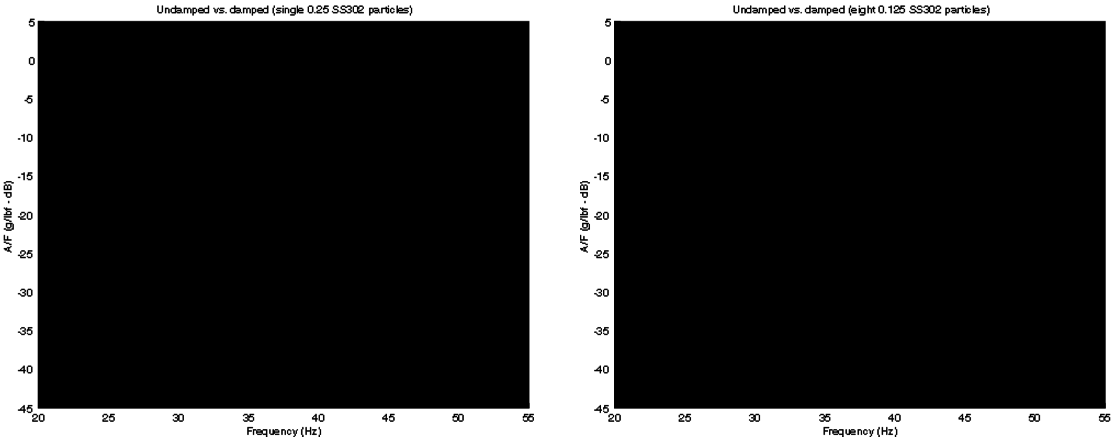


**FIGURE 49.** Undamped to Damped Comparison for Single and Multiple-Particle Tests

**FIGURE 50.** High-Temperature Test Articles

**Participating Organizations: CSA** Engineering, Inc., University of Dayton Research Institute

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## 6.1.5 Centrifugally Loaded Particle Damping

***FY 96-00***

**Recent Progress:** During the past year, significant progress was made in several areas critical to understanding particle damping and its potential for use in the rotating engine components, including:

- Characterization of the relevant dynamic disturbance environment
- Development of explicit analytical modeling/predictions tools
- Expanded experimental test methods and systems
- Improved data analysis and extraction tools

Particle damping is dependent on the motion of particles inside a cavity. If the disturbance levels are low, the particles cannot overcome friction and will not move. While experimental results clearly show damping effectiveness in the laboratory, it was not well understood how much dynamic acceleration occurred in engine blades. Without this information it was impossible to determine if particle damping treatments had a chance of overcoming the high friction forces caused by the centrifugal loads. The issue of actual disturbance levels has been resolved. Examination of the achieved disturbance levels in various centrifugally loaded tests performed by us and others revealed that actual achieved levels were lower than what would be experienced in an engine. An effort to experimentally identify the "turn-off" ratio has begun for a wide range of particle and cavity types relevant to the rotating engine components and temperature extremes, thus enabling more focused centrifugally-loaded spin testing. Preliminary results have shown that the treatments that give the best damping tend to "turn off" sooner than treatments that give slightly lower but still very acceptable damping.

Analytically, the capability to explicitly model the behavior of multiple particles, taking into account impact and frictional loss mechanisms was further developed. Methodologies were also developed to generate estimates of a blade's maximum allowable acceleration at any given point based on the blade's allowable fatigue limits. In the area of data extraction and analysis, improved methods for estimating amplitude dependent damping were developed based on the Hilbert transform. An example is shown in Figure 51.

Experimentally, efforts have concentrated on developing new test capabilities that will safely allow rapid testing of various particle damping concepts in the laboratory. The developed test system, which is currently being integrated (see Fig. 52 for some of the hardware) will allow particle damping treatments to be exposed to over 75,000 g's while being dynamically excited by piezoelectric patches. High g tolerant accelerometers will provide data up to 10,000 g's load, after which other piezoelectric-based sensors will be used. Additionally, experimental tests of limited scope were performed at low centrifugal loads for three capsule configurations.

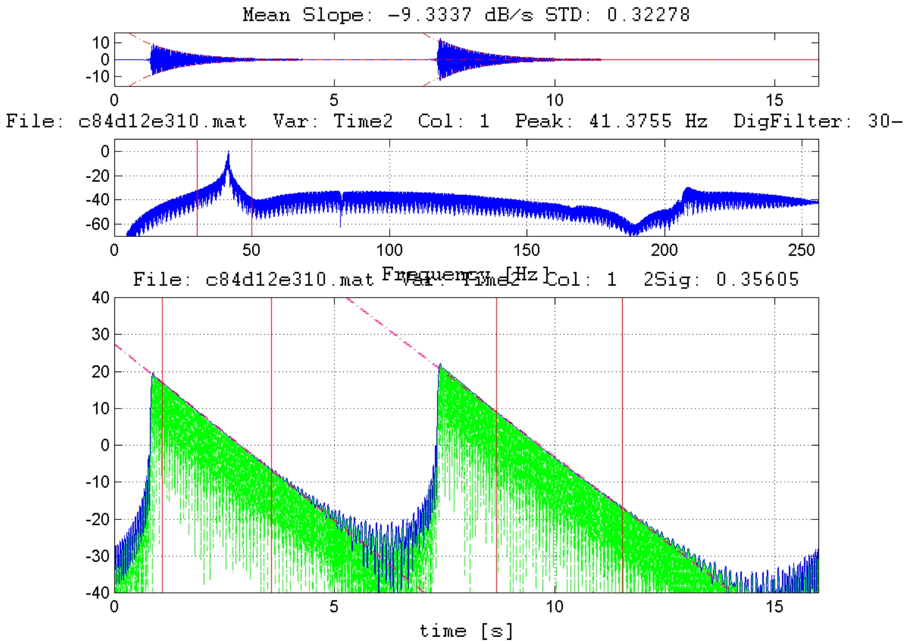


**FIGURE 51.** Example Time Domain Ring Down and Extracted Hilbert Transform Profile with Linear Fits for a Baseline Non-Damped Test Object

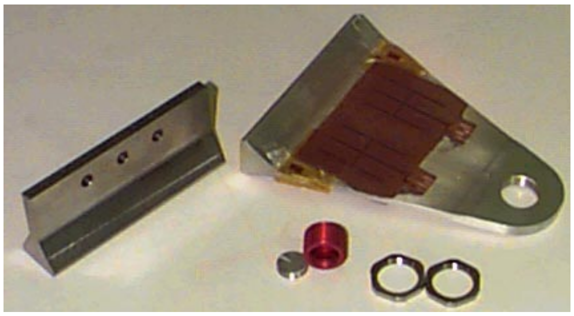

**FIGURE 52.** Phase II Blade, Counterbalance, and Test Capsules Prior to Blade Wiring and Encapsulation

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## 6.2 Modeling and Incorporation of Damping in Components

Of the four types of damping systems (friction dampers, viscoelastic damping systems, particle dampers, and powder damping systems), two were ready for use in the design of rotating components: friction and viscoelastic damping systems. A program was initiated to use friction dampers for lower-order modes and to establish their ability to damp higher-order modes. Although there were some concerns with using viscoelastic materials, it was decided that a design program should be started while final characterization of viscoelastic materials was pursued. Component design work for particle and powder damping systems was considered premature, due to a lack of knowledge and a lack of confidence as to the likely performance of either system in a centrifugal environment. Design and testing of components with these systems will occur in the future.

### 6.2.1 Advanced Damping Concepts for Reduced HCF
*FY 96-00*

**Background:** The objective of this task is to design damping into integrally bladed rotors. The new damped design will then be validated with a spin test. Although the original focus of this program was hollow fan blades, the program has been redirected toward concepts applicable to both hollow and solid blades. This change has occurred because of the increasing reliance of the manufacturers on rotors with solid blades.

Information has been gathered to define damping level requirements and the operational environment for a damping system. Team members Pratt & Whitney (P&W) and Honeywell Engines and Systems have provided environmental definition information including operating speeds, temperatures, and frequency ranges to the University of Dayton Research Institute (UDRI). They also have provided documentation regarding current and future blade systems and finite element models of typical blade designs.

Based on discussions with the Air Force, the UDRI/P&W/Honeywell team developed a list of damping concepts applicable to rotating bladed turbine engine hardware. A Delphi analysis was used to rate each of the damping concepts with respect to each of the evaluation criteria. The criteria were selected by the team to fairly address the effectiveness, reliability, and manufacturability of each of the concepts. All the evaluation factors were weighted evenly. The results of the Delphi analysis are indicated in Figure 53. Based on the assessment, the team and the Air Force decided to pursue detailed design and demonstration of a constraining layer rim damping (CLD) concept.

The rim damping concept will be demonstrated on a P&W Fan integrally bladed rotor (IBR). The target mode is the third leading edge (3LE) bending in the blade coupled with the nine nodal diameter bending of the rim. Several leading edge and trailing rim damping design concepts were developed by UDRI and reviewed by P&W with regard to manufacturability and clearance issues. Based on technical review among the team members, specific changes to the leading edge of the IBR were selected that will allow the damping concept to be applied to a surface that is cylindrical. For this particular IBR, the trailing edge rim is cylindrical and no changes are required for attaching the damping concept.

A finite element analysis (FEA) model of the IBR, which had previously been validated by P&W, was modified by UDRI to simulate the addition of a damping system. The FEA was used to evaluate two general conditions: expected effectiveness in damping vibrations and expected ability to withstand centrifugal loads. First, resonant frequency computations were performed over a range of viscoelastic material shear stiffness values. These analyses were used to optimize the strain energy ratio as a function of viscoelastic material shear stiffness for the 3LE bending mode.

Time and temperature data provided by P&W indicates that the optimal damping temperature should be 225°F for this IBR, and the survival temperature is 600°F. Because of the 375°F difference between operating temperature and survival temperature, a material like silicone will be needed to handle the temperature range. Unfortunately, silicone has a relatively low inherent material loss factor, on the order of 0.1. To obtain a significant damping level for the 3LE bend mode, the stiffness of the viscoelastic in the CLD system has been optimized to range where the CLD operates as a tuned damper, resulting in a large portion of the system strain energy being transferred into the viscoelastic. Efforts are ongoing to formulate a silicone that has the desired stiffness, temperature capabilities, and creep resistance.

Another issue is the stresses under centrifugal loading. The FEA indicates that steady stress levels in the most highly loaded areas are nearly unaffected by the addition of the damping system. However, the analysis indicates that a damping system with many segments is required to ensure acceptable strain levels in the viscoelastic due to radial growth of the rim under centrifugal loads. To reduce strain in the viscoelastic material under centrifugal loading, the titanium cover, which is acting as a mass for a tuned damper rather than as a typical constraining layer, will be segmented into pieces around the circumference of the rim.

During the next year, an IBR will be modified and a damping system installed. Bench testing will be used to assess the damping characteristics over a temperature range from 75°F to 300°F, which is the temperature range in which this IBR typically operates. A spin test will be performed at temperatures up to 600°F to assess survivability at high temperatures under centrifugal loading.

| Damping Concept | Existing Technology Knowledge | Ease of Manufacture | Reliability | Transitionability to Existing Designs | Solves Mistuning Problems | Solves High-Frequency Resonance Problems | Solves Flutter and Surge Problems | No Performance Impact | Capability to Meet Environ. Conditions | Raw Score | Ranking |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Constraining Layer Rim Damping | 4 | 4 | 4 | 4 | 3 | 1 | 4 | 5 | 3 | 32 | 1 |
| Rim Friction Damping | 3 | 4 | 3 | 4 | 3 | 1 | 4 | 5 | 5 | 32 | 1 |
| Damping Pocket With Cover Plate | 4 | 3 | 3 | 3 | 3 | 2 | 4 | 4 | 3 | 29 | 2 |
| Cast Damping Into Airfoil Cavities | 4 | 2 | 3 | 1 | 4 | 4 | 4 | 5 | 3 | 29 | 2 |
| Leading/Trailing Edge Sheathing | 3 | 2 | 2 | 3 | 4 | 4 | 4 | 3 | 3 | 28 | 2 |
| Rim Piezoelectric Damping | 2 | 4 | 2 | 4 | 3 | 1 | 4 | 5 | 3 | 28 | 2 |
| Particle Damping | 2 | 3 | 3 | 3 | 3 | 1 | 4 | 4 | 5 | 28 | 2 |
| Surface Coatings | 2 | 3 | 2 | 3 | 3 | 4 | 4 | 2 | 3 | 26 | 3 |

Scale: 5=Excellent to 0=Bad

**FIGURE 53.** Delphi Analysis of Damping Concepts

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## 6.2.2 Damping System for Integrated High Performance Turbine Engine Technology (IHPTET) Program

***FY 97-00***

**Background:** The Damping Systems for the IHPTET Components program is a thirty-six month technical effort that was initiated in January 1997. The purpose of this program is the design, fabrication, instrumentation, bench testing, and spin testing of two damping systems, one for each of two blisk components. The specific objective of the design is to achieve effective magnification factors (Q) of approximately 50 or less for the targeted modes of vibration. The testing will demonstrate damping effectiveness and validate that the damping systems can reliably work under static and dynamic loads produced in a simulated turbine engine environment. Mr. Frank Lieghley, Jr., USAF Project Engineer, is administering this contract within the USAF.

Fabrication and inspection of the viscoelastic constrained layer damping system in all 16 airfoils of the Advanced Core Compression System (ACCS) blisk was completed (Fig. 54). Bench test results showed that significant damping was achieved, but damping was somewhat short of the goal. X-ray inspection revealed that the laser welds of the titanium coversheets did not achieve the desired 100% penetration. It was judged that the welds were adequate, but that we should conduct an overspeed proof test. Instrumentation was completed, and the damped blisk was shipped to Test Devices for spin testing. The proof spin test of the Allison ACCS damped blisk was conducted. During the attempt to attain the proof spin speed of 20,000 rpm, a shift in rotor vibrations was noticed at 15,000 rpm. The rig was shut down and inspected. It was found that three (of 32) titanium coversheets had partially failed in the region of laser weld (Fig. 56). In addition, two of the stainless steel constraining layers were released from the rotor. The blisk was sent to AADC for further inspection. The inspection revealed that an additional eight coversheets had visible weld cracks. The failure analysis concluded that a radial shift of the constraining layer caused a "wedging" load that failed the coversheet weld. As a result, testing of this design was suspended and Phase II of the contract is being replanned.

**FIGURE 54.** Damped ACCS Blisk

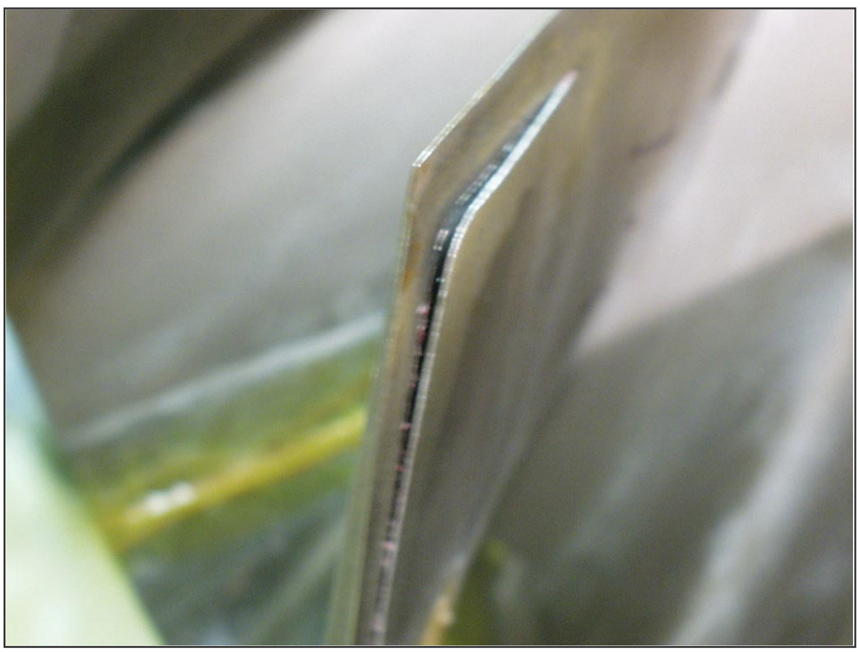

**FIGURE 55.** Weld Failure

**Participating Organizations:** General Electric Aircraft Engines, Rolls Royce Allison, Roush Anatrol

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## 6.2.3 Evaluation of Reinforced Swept Airfoils / Internal Dampers

***FY 96-00***

**Background:** The objective of this project was to develop and spin test a friction damper for fans. The internal friction damper was designed and analyzed to maximize the damping characteristics of this damping system. The primary function of this design was to demonstrate its effectiveness in reducing the vibratory responses of selected high-order modes. A finite element design utilizing the friction damper was completed, a damping prediction analysis was performed on the component, and the analytical model was verified with static bench test data.

**Recent Developments:** The spin test was cancelled when it was determined that the likelihood of this component ever being placed into production was very limited. It was decided to redirect the program to address damping of integrally bladed rotors (IBRs). It has been aligned with the UDRI task on "Advanced Damping Concepts to Reduce HCF of Hollow Fan Blades" (see Section 6.2.1). The selected approach has been narrowed down to under-rim viscoelastic damping treatment.

Preliminary testing of this approach on a solid fan IBR has demonstrated good potential for modes with sufficient rim strain energy contribution. Concept demonstration of bench testing of the IBR in a 3$^{rd}$ LE bending mode resulted in a 20% reduction in response. This approach will be optimized for the real engine environment. Damping assessments will be demonstrated using bench testing only since the centrifugal loading will be designed to be perpendicular to the damping treatment. Survivability testing, however, will be demonstrated in a heated spin test facility. Upon completion of the spin tests, a repeat of the bench damping tests will be conducted to ensure that damping effectiveness still exists after exposure to the elevated temperature spin test.

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## 6.2.4 Damping for Turbines

*FY 97-00*

**Background:** The objective of this project is to develop new damping systems for turbines verified with spin-pit tests.

Damping improvements will provide increased design space for more-optimal blade and turbine stage designs. This will reduce aeromechanical risk for turbines and potentially, for other aeromechanical structures. Allowing simultaneously reduced weight and increased durability.

**Recent Developments:** A unique damping system has demonstrated stress reductions of up to 80% (damped/undamped x 100) alternating stress. This damping technology will enable new configuration designs to become viable by lowering blade stress response in expectedly harsher environments. With additional development and predictive modeling, the damping technology may routinely be used to enable even further reduced-weight rotors and engine systems.

Damper performance data has been obtained by spin testing in a unique HCF-driver spin-rig to generate information on several vibration modes of a blade. The variations of the experiments were designed to depend totally on the damping process under development without the involvement of other damping processes. Additionally, the approaches used to obtaining this data are innovative, while also providing repeatable and controlled drivers and responses above 20,000 Hz frequency.

Future Navy plans for FY00 involve the re-characterization of the damper's performance after exposure in a demonstrator engine. This will validate the durability of a particular design and add further to predictive models.

**Participating Organizations:** Pratt & Whitney

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## 6.2.5 Dual Use Program

*FY 00-01*

**Background and Plans:** This program will provide damping improvements required to support advanced engine configurations. This will be accomplished by using rapid casting hardware fabrication techniques to generate rig hardware. The development of a verification method relying on rapid prototyping will reduce technology development cycle times. By providing designs rapidly, technology and innovation can be more readily proved out. This will allow marked progress toward improving damping, and delivering designs that meet program goals or requirements. It is not enough to develop new concepts, but these must be fully integrated into advanced cooled turbine blades. The key to developing advanced damping approaches is marrying the damper and blade design to the manufacturing process.

**Participating Organizations:** Air Force Research Laboratory (AFRL), Pratt & Whitney Aircraft

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## 6.2.6 Transition of Damping Technology to Counterrotating Low-Pressure Turbine Blades

*FY 00-01*

Counterrotating turbine designs subject the low-pressure turbine (LPT) blades to high-frequency excitation from the high-pressure turbine blades immediately upstream. The vibratory response of the LPT blades is in a high-order airfoil mode for which typical platform friction dampers used for lower modes are less effective. This contract addresses innovative damping concepts to provide damping for higher-order LPT turbine blade airfoil modes.

The Contract consists of two Tasks. In Task 1, GE Aircraft Engines, working with subcontractors, Roush Anatrol Division of Roush Industries and Allison Advanced Development Company, will design and provide simple test specimens with two different damping treatments to the USAF for elevated temperature testing. The Turbine Engine Fatigue Facility (TEFF) at the U.S. Air Force Research Laboratory will contrast damping performance of the two treatments for selected airfoil modes of vibration with untreated baseline specimens. In Task 2, a preferred damping treatment will be selected, based on the Task 1 test results, and applied to prototype LPT blades. These blades will then be tested at elevated temperature at the U.S. Air Force TEFF.

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## 6.3 Conclusion

By conducting rig, component, and engine tests, and by developing very successful modeling techniques, the Passive Damping Technology Action Team has evaluated numerous damping schemes with great potential. The Team has demonstrated that the historically-based "rainbow" or mixed wheel concept is not an acceptable test protocol for HCF modal damping investigation, and that designing a viscoelastic damping system insertion into a mechanically sound rotating blade may be more difficult than it appears. This team has also demonstrated the feasibility of applying viscoelastic damping to the rim of a bladed rotor rather than to the blade surface. Doing so could effect an 80% reduction in blade stresses. Completed initial tests of an internal "dip stick" friction damper for turbine blades also demonstrated up to 80% stress reduction. The turbine friction damping effort has been a major success, with test results showing vibratory reductions much greater than predicted. The turbine damper is currently being applied in an advanced engine development program. Manufacturability of damping solutions is being evaluated as a major area of future emphasis.